Multidomain Suppression of Ambient Light in Visible Light Communication Transceivers

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***Abstract*—Visible light communication (VLC) transceivers suffer from optical interference and ambient light saturation, which severely affect the reception of optical signals. In this paper, we discuss various techniques for the suppression of ambient light in electronic, optical, communication and wavelength domains with focus on VLC systems for vehicular communication. Designing transceivers for outdoor VLC systems is challenging due to the dynamic environment and the time-varying nature of interference from different types of ambient light sources. This is a unique study that addresses the problem of optical interference in multiple physical domains and offers qualitative insights in a systematic manner.**

***Index Terms*—Visible light communication, moving transceivers, ambient light saturation, optical interference, polarization.**

I. Introduction

VISIBLE light communication (VLC) has gained significant research interest as a complimentary technology to radio frequency (RF) communication [1], [2]. Key benefits of VLC over RF communication include the availability of free (unlicensed) spectrum, wide bandwidth (400 – 800 THz), and low interference and latency. Some of the popular applications of VLC are indoor positioning or localization as a more accurate alternative to GPS [3], [4], Li Fi as a supplementary technology to Wi Fi for high data rates (Gbps) [5], and vehicular communication in intelligent transport systems (ITS) [6], [7].

VLC systems involve the transmission and reception of optical signals in a noise-free manner in free-space medium.

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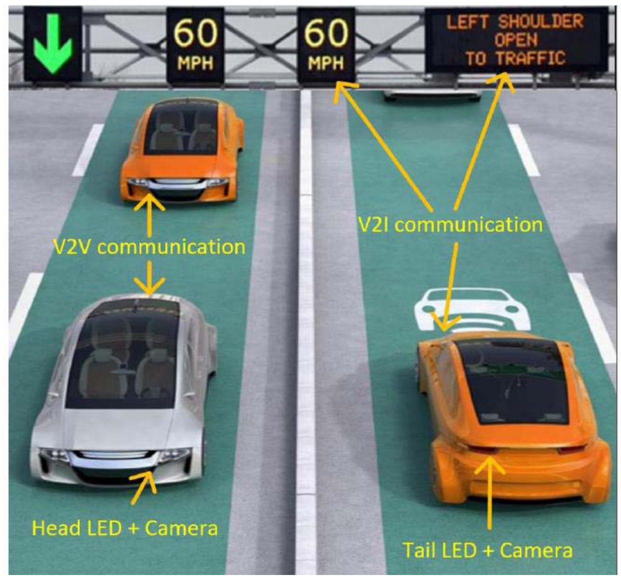


Fig. 1. Visible light communication scenarios for outdoor application, e.g. intelligent transport systems (ITS). V2V (vehicle to vehicle) and V2I (vehicle to infrastructure) communication are shown as potential applications in ITS.

Compared to indoor, the outdoor application of VLC systems faces greater challenges in terms of background light interference. Strong solar irradiance during the day and other light sources at night may severely degrade the reception of optical signals. In recent years, VLC has emerged as a popular technology supplementing RF communication for automotive applications [8]. A multitude of technologies such as ultrasound sensors, depth cameras, Lidar, Radar, and visible light communication (VLC) transceivers integrating in a complementary manner will shape the future of autonomous vehicles. Furthermore, the co-integration of vision sensors with machine learning algorithms will accelerate the emergence of autonomous vehicles sooner than later [9].

Today's automobiles come pre-fitted with daytime running lamps (DRL) and parking cameras which may readily be utilized for VLC communication to provide a complimentary technology of communication among vehicles (V2V communication) [10] or between vehicles and traffic infrastructure (V2I) [11] as shown in Fig. 1. Without loss of generality, the visible light vehicular transceivers also suffer from background light interference [12], which in some cases may entirely saturate the receiver.

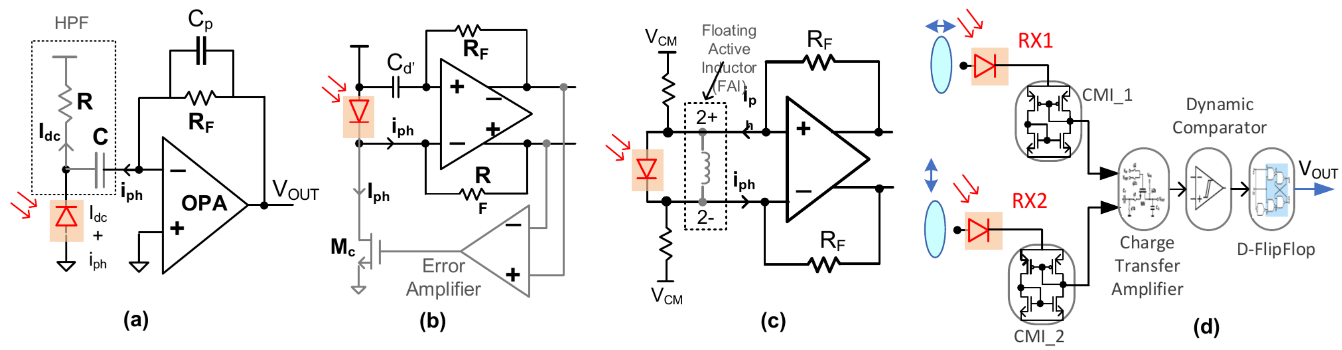


Fig. 2. (a) Resistive TIA with passive RC filter at the input to filter ambient light, (b) resistive TIA using active feedback loop from TIA output to input, (c) resistive TIA with DC photocurrent shunting via an active inductor, (d) a current-mirror based differential channel receiver exploiting the polarization property of light followed by a charge transfer amplifier to reject the ambient light.

In this paper, we will discuss diverse methods to address the issue of ambient light interference in multiple physical domains. We will also compare the pros and cons of these methods and offer insights and recommendations for their deployment in different situation. In general, all methods discussed in this paper are applicable for the ambient light suppression in outdoor environment but we focus on vehicular communications as it is among the most attractive use cases for outdoor VLC systems, due to the high level of global investments in intelligent transportation systems and autonomous vehicles. This use case is also technically challenging due to the dynamic nature of the environment resulting from the mobility of the vehicles and leading to time-varying ambient light interference [13]–[15].

The ambient light suppression methods in electronic domain are discussed in Section II followed by the optical methods to get rid of optical interference in Section III. Section IV presents some modulation schemes in communication domain which are significantly tolerant to optical noises. In Section V, we discuss a novel approach of ambient light suppression in wavelength domain. Section VI presents a qualitative discussion of all these methods and underscore the efficacy of hybrid or integrated approach to suppress optical noise in multiple domains. Section VII concludes the paper.

II. Ambient Light Suppression in Electronic Domain

Over the years, many circuit-level techniques have been proposed to shunt or suppress the DC photo current originating from the ambient light or other optical interference sources. Generally speaking, the optical front-end circuits implemented in CMOS technologies have benefited from the constant improvements in advanced process nodes (being able to operate at higher frequencies and enable higher data rates) [16]–[20]. Visible light transceivers in automotive applications do not normally require high data rates [12]. Robust suppression of background optical noise and increasing the communication distance for V2V and V2I applications are the two foremost challenges in this area [21].

VLC receivers may be implemented with CMOS image sensors (CIS) or as photodiode-based circuits. The CIS-based VLC receivers are inherently better at separating signal from the ambient light [22]–[25] at pixel-level in addition to being able to detect multiple transmitters and therefore support multiple-input multiple-output (MIMO) communication [26], [27]. However, they are relatively costly. On the other hand, photodiode-based VLC receivers can be made at lower costs but they require additional (and more complicated) methods to remove the ambient photocurrent [28]. For this study, we will focus on the ambient noise suppression in photodiode based VLC receivers.

Traditional optical receivers are often based on resistive transimpedance amplifier (TIA) as shown in Fig. 2(a). This architecture suffers from high power consumption of the operational amplifier and complex trade-offs between the TIA bandwidth and transimpedance gain. For instance, in Fig. 2(a), high gain requirement entails a large value of feedback resistor R_F but this would also reduce the TIA bandwidth by bringing the non-dominant pole towards low-frequency according to (1).

$$V_{\text{out}} = -I_{ph} \cdot R_F \cdot \frac{1}{1 + s \cdot R_F C_p} \tag{1}$$

Here, C_p is the parasitic or stray capacitance of the feedback resistor and its value increases proportionally with large values of R_F. Moreover, to suppress the DC photocurrent originating from the ambient sunlight, a high-pass filter is required at the TIA input to steer clear of this current from saturating the VLC receiver. In order to enable low value of high-pass corner frequency, chip-level implementation of large values of resistor and capacitor is also not feasible for being too expansive. Another disadvantage of the circuit presented in Fig. 2(a) is the value of photodiode bias being dependent on the signal photocurrent which will change during the circuit operation and introduce signal-dependent errors [29].

The active feedback loop in Fig. 2(b) is a better circuit for the reduction of DC photocurrent as it avoids the earlier drawbacks of Fig. 2(a). This topology offers a better regulation of TIA gain, bandwidth and photodiode bias voltage. However, the thermal noise of compensation transistor M_c directly adds in the signal path and reduces the maximum achievable signal-to-noise ratio (SNR) of this circuit.

Recently, we presented a TIA circuit as shown in Fig. 2(c), which uses a floating active inductor to shunt the DC photocurrent from ambient sunlight and allows only the signal photocurrent with high-frequency component to pass through

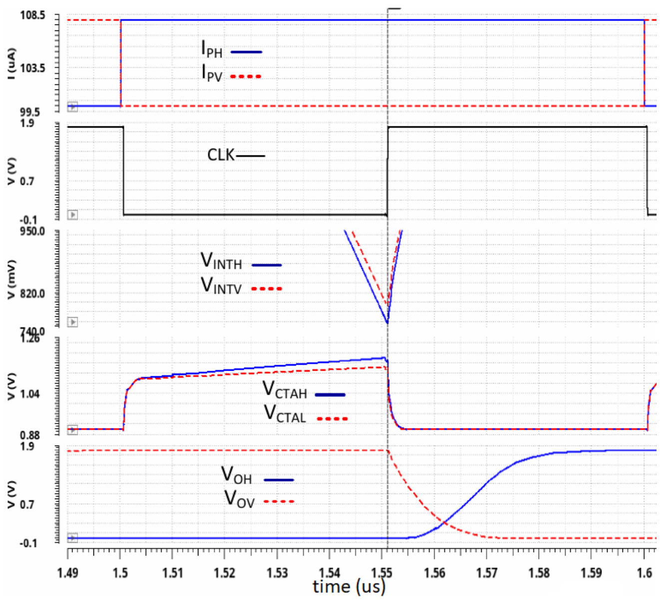


Fig. 3. Transient simulation response of major nodes of the circuit shown in Fig. 2 (d) [27].

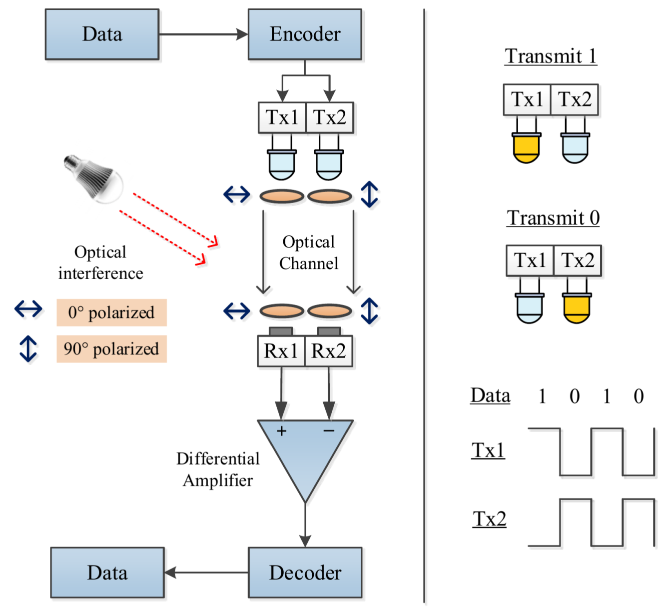


Fig. 4. System architecture of the polarization-based interference-tolerant VLC link for low data rate applications.

the gain-setting resistor R_F around the TIA [30]. Although the circuit works for low to medium data rate applications, it may not be practical for high-frequency applications. Also, the bias voltage of the photodiode is hard to regulate in this topology. Nevertheless, in Cadence Spectre simulations, our design achieves a transimpedance gain of 98 $d B\Omega$ from 1.5 kHz to 2.5 MHz (3-dB) bandwidth in the presence of up to 50 μA DC photocurrent [30].

We have implemented another design where ambient light suppression of up to 100 μA has been demonstrated [31]. As shown in Fig. 2(d), a complementary set of linear polarizers is used to transmit and receive the optical signal in a complementary manner such that the optical signal received by RX1 and RX2 is mutually exclusive to each other. This means the optical signal from one transmitter is only received by RX1 and practically blocked by RX2 and vice versa. In addition to optical background noise suppression via polarization property of light, a differential charge transfer amplifier used in the later stage of VLC receiver also obtains common-mode rejection of the optical signal in electronic domain. Any background interference common to both receiver nodes is cancelled out. The transient response of this circuit is shown in Fig. 3. The two photodiodes at RX1 and RX2 both convert the incident light into differential signal photocurrent I_{PH} and I_{PV} (8μA) in addition to a large DC photocurrent of 100μA (that correspond to ambient light signal). The photocurrents are integrated over a set of integration capacitors through corresponding CMI (Current Mirroring Integration) circuits to gather the integrated voltages V_{INTH} and V_{INTV} respectively. Any voltage common to both receiver nodes is cancelled by the differential operation of charge transfer amplifier and the rail-to-rail output voltage is resolved by D flip flops as shown by V_{OH} and V_{OV} in Fig. 3.

Sunlight induced shot noise in electronic components of the receiver front-end may be mitigated by optical filtering [32], selective receiver combining [33], or by varying the optimum receiver bandwidth with the temporal changes in ambient light and daytime [34]. Adaptive differential equalization has been used to reduce the effect of optical interference and shot noise caused by the ambient light on the VLC receiver's SNR [35]. Similarly, [36] proposed an average voltage tracking circuit to detect and cancel the noise voltage produced by ambient light sources in low SNR receivers.

III. Ambient Light Suppression in Optical Domain

Considerable research has been performed on the application of optical filters and lenses to mitigate the interference produced by optical sources present in the vicinity of the receiver [32], [37], [38]. However, the utilization of optical filters imposes restrictions on the incident angle of the incoming light. This phenomenon limits the possible applications of the proposed transceiver architecture. A Fresnel lens was used by Y. H. Kim [39] at the receiver end to increase the signal-to-noise (SNR) ratio under foggy weather conditions. However, the performance of the system was not evaluated under bright optical sources causing interference in the optical link.

Polarization is a fundamental property of light which may be used to filter unwanted light (e.g., sunlight) in all but one direction using, for instance, 0° and 90° polarizers. We implemented a transceiver architecture that incorporates differential data transmission and reception by exploiting the polarization property of light [40], [41]. The stream of incoming binary data is first encoded using a complementary data generator. The complementary data is then used to drive two separate optical front ends, namely Tx1 and Tx2. Tx1 will be turned ON only if the data bit to be transmitted is a '1'. Similarly, Tx2 will be turned ON only when the data bit to be transmitted is a '0'. Linear polarization filters are then used to polarize the emitted light for minimizing optical interference. The system level architecture is shown in Fig. 4.

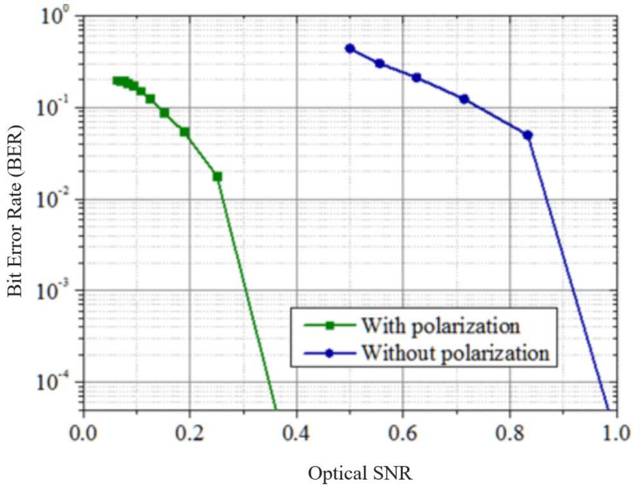


Fig. 5. BER vs. optical SNR in the presence of active interference [33].

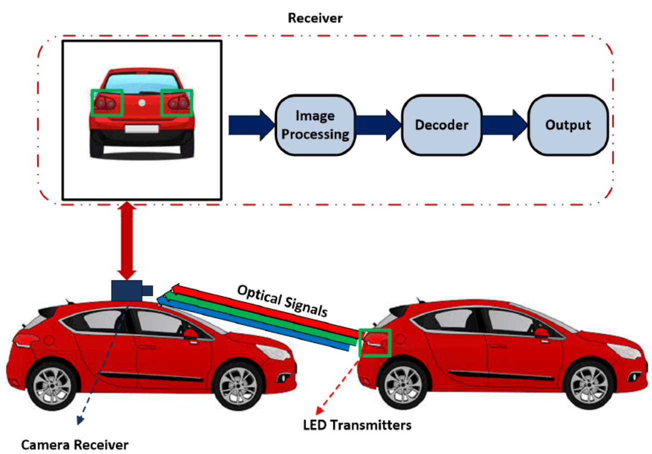
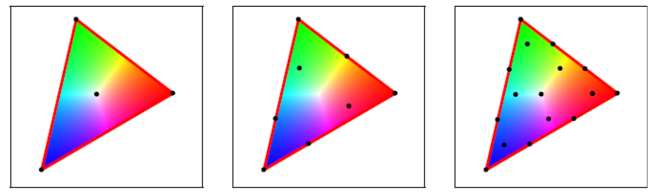


Fig. 6. End-to-end vehicle-to-vehicle VLC system with CSK transmitter and camera-based receiver.

Two separate receiver front ends, Rx1 and Rx2, are used to receive complementary data transmitted by Tx1 and Tx2, respectively. The polarization filters are configured between transmitter and receiver in such a way that a communication channel is established between Tx1/Rx1 pair and Tx2/Rx2 pair only. The Tx1/Rx1 pair utilizes 0^o linear polarization whereas the Tx2/Rx2 pair utilizes 90^o linear polarization. This configuration ensures that the light emitted by Tx1 is blocked by the linear polarizer of Rx2 and the light emitted by Tx2 is blocked by the linear polarizer of Rx1. Differential amplification of Rx1 and Rx2 is then performed to extract the transmitted data. Any background optical interference, reaching Rx1 and Rx2 with equal intensity, will be removed by the common-mode rejection ratio of differential amplifier. We conduct an experiment in the presence of active interference by transmitting random binary data in the similar frequency band as our signal data in Fig. 4. The corresponding bit error rate (BER) plot versus optical signal to noise ratio (SNR) is plotted in Fig. 5. The green plot of Fig. 5 indicates that by using the polarization based VLC link, similar BER level can be achieved at much lower optical SNR even in the presence of active noise source [40]. In this figure, the SNR is obtained by dividing the optical received power of the signal by optical ambient light power. Other electrical noise sources were not considered. More precisely, these were empirical values of signal illuminance divided by ambient light illuminance as measured by lux meter inside a lab environment.



(a) IEEE 4-CSK (b) IEEE 8-CSK (c) IEEE 16-CSK

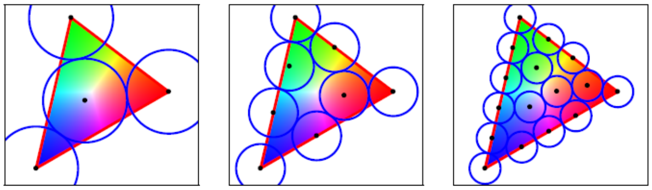
Fig. 7. IEEE 802.15.7 standard CSK constellation sets.

IV. Ambient Light Suppression in Communication Domain

In VLC systems, a wide range of techniques can be used to modulate the information from LED transmitters (e.g., see [42] and the references within), and a photodiode (PD) array or a CIS camera can be used to process the optical signals at the receiver side. Selecting an appropriate modulation technique helps in the suppression of optical interference. The effect of using Manchester encoding [43] and OFDM modulation [44] on the robustness of VLC links in the presence of optical interference has been studied before. The IEEE 802.15.7 standard for wireless optical communications includes three modulation techniques [45]: On-Off Keying (OOK), Variable Pulse Position Modulation (VPPM), and Color Shift Keying (CSK). The latter is most suitable for high data rate applications and multi-vehicle scenarios, with favorable robustness characteristics (e.g., see [46]).

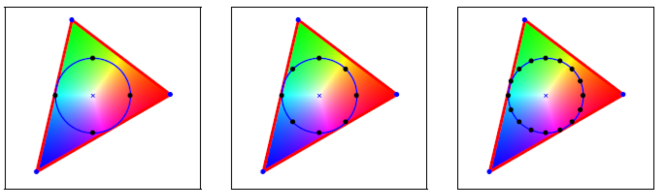
The simplest binary modulation scheme is OOK, where the bits 0 and 1 are transmitted by turning the LEDs off and on, respectively. VPPM extends OOK through adapting the dimming level of the LEDs, which can provide performance advantages in dynamic environments such as vehicular communications. Pulse Amplitude Modulation (PAM) schemes generalize OOK to higher order modulation schemes with more than two intensity levels, which achieves higher bit rates but suffers from less resilience to ambient noise interference. While these modulation schemes have relatively low complexity transceiver designs, they do not make full use of the luminous nature of the transmitted light signals in VLC systems. In [47] and [48], we have presented an end-to-end VLC physical layer design with novel CSK modulation schemes and camera based receivers (see Fig. 6), to overcome both the background noise capturing ambient light in the environment and the directional noise capturing parasitic light sources such as street or other vehicles lights.

CSK allows data transmission through color variations, with constellation points mapped to multiple colors on the color space formed by different red, green, and blue intensity combinations. Fig. 7 shows the IEEE 802.15.7 Standard constellation



(a) GEO 4-CSK (b) GEO 8-CSK (c) GEO 16-CSK

Fig. 8. Geometrical CSK constellation sets.



(a) CIRC 4-CSK (b) CIRC 8-CSK (c) CIRC 16-CSK

Fig. 9. Circular CSK constellation sets.

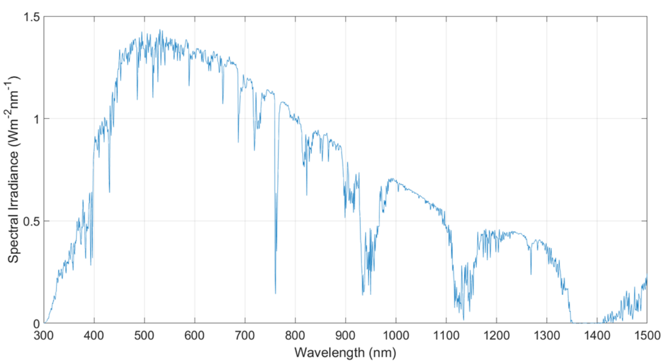


Fig. 10. Airmass 1.5G sunlight spectrum [49].

sets, whereas Fig. 8 and Fig. 9 show the proposed geometrical and circular constellation sets respectively. The geometrical constellation set achieves resilient performance against ambient light noise sources by spreading the constellation points uniformly to maximize the minimum Euclidean distance between neighboring points. On the other hand, the circular constellation set spreads the constellation points around a circular region, taking into account the fact that ambient noise typically pushes the received color towards the white zone at the center of the color space. In this case, the performance at the receiver side is based on the angular dimension between the different constellation points.

Simulation and analytical performance results demonstrate the effectiveness of the proposed CSK modulation schemes compared to OOK and the IEEE 802.15.7 Standard CSK constellation set [48], in terms of signal to noise ratio level and resilience against ambient noise as a function of data bit rate and distance between the communicating vehicles.

V. Ambient Light Suppression in the Wavelength Domain

The irradiance from sunlight varies considerably with wavelength, as can be seen in Fig. 10, which shows the Air mass 1.5G spectrum for sunlight [49]. Therefore, in addition

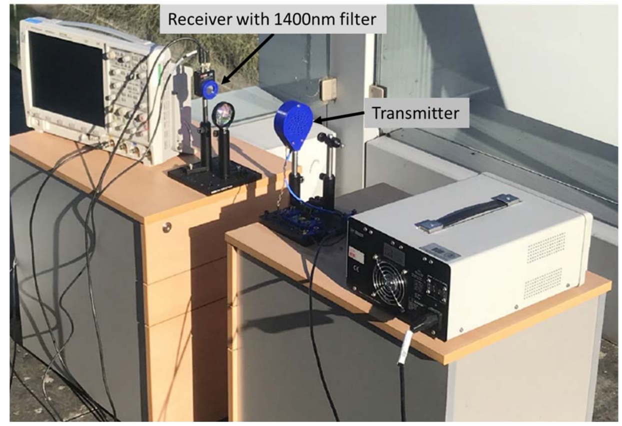


Fig. 11. 1400 nm link in direct sunlight conditions.

to the previous approaches, selected wavelengths could be used for robust free-space communications between vehicles. Compared to the visible wavelengths, a substantial reduction in ambient sunlight could be achieved by operating an optical link between 1350-1410 *nm*. This is due to absorption by water vapor within the atmosphere [50]. For a link with a 12 *nm* optical bandwidth centered at 1400 *nm*, a reduction in ambient sunlight power of 32.1 *dB* might be achievable compared to a 12 *nm* channel centered at 450 *nm*.

Such a link has been explored for Quantum Key distribution [51], but to the best of our knowledge there has been no consideration for automotive communications. For this study, a 1400nm link for the automotive environment was simulated, and a practical implementation demonstrated. The simulations compared a 450 *nm* link, modelled based on automotive lighting units, to a power-equivalent 1400 *nm* link. This work showed that the 1400 *nm* link was considerably more robust to the effects of sunlight than the 450 *nm* link. The range of the 1400nm link is significantly affected by the water content of the atmosphere, a function of temperature and relative humidity, but useful ranges (50 *m – 100 m*) could still be achieved in simulated high water content environments.

In order to test the concept, a link operating at 1400nm was implemented and tested outdoors. The transmitter was based on four InGaAsP LEDs (Thorlabs, LED1450L), producing an output power of 5 mW and bandwidth of 5MHz, transmitting a 4096-bit sequence at 10Mb/s using Non-Return-to-Zero On-Off Keying. A commercial InGaAs TIA based photo receiver (Thorlabs PDA20C/M), was used to detect the incoming radiation, and a 12 nm bandwidth optical filter centered at 1400 nm was used (Edmund optics #65-790) to limit the sunlight spectrum reaching the detector. The receiver Bandwidth is 5MHz with an active detection area of 3.14mm^2. In order to allow sunlight to fall directly onto the receiver, no collection lens was used in the experiment, limiting the link length to 0.25m. The received power in this setup was measured to be $0.6\mu W$. Fig. 11 shows a picture of the experimental setup. The link could be maintained outdoors at direct ambient sunlight levels of 81000 *lux* approaching the highest illuminance expected in the automotive environment.

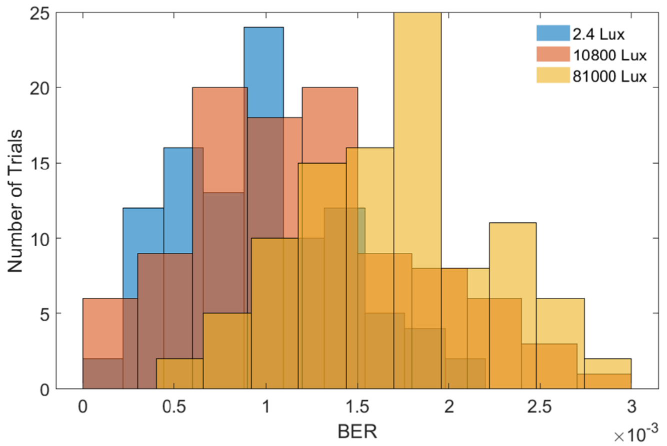


Fig. 12. BER histograms for night (2.4 lux), typical daylight (10800 lux) and direct sunlight (81000 lux) conditions for the 1400 nm link over *a* link distance of 0.25m.

As seen in Fig. 12, the mean BER of the link, collected over 100 trials, did not substantially change between dark conditions and direct sunlight incident onto the receiver. In dark conditions (2.4 lux), the mean BER in 100 trials was 9.4×10^{-4}, with a standard deviation of 5.1×10^{-4}. In direct sunlight conditions, the increased ambient light induces a rise in mean to 1.7×10^{-3} with a standard deviation of 5.9×10^{-4}. As such, the observed variations between dark and direct sunlight are within 2σ of each other.

This is to the best of the authors' knowledge the first time that a 1400 *nm* region optical link has been demonstrated in the outdoor environments. This work shows that the selection of communication wavelengths with a low ambient irradiance is a promising approach to utilize in optical vehicular communication for operation in daylight conditions. With further development, the employment of a 1400 *nm* link could operate alongside other visible channels discussed in this paper to provide a robust communication system.

VI. Discussion and Future Directions

For effective and efficient implementation of a robust VLC link, a complete system-level evaluation of the ambient light suppression is required. This evaluation should consider the limitations and strengths of each method in each physical domain. There may be opportunities for hybrid implementation of two or more such methods in a single transceiver system, i.e., a VLC receiver employing circuit-level cancellation of background light coated with on-chip polarization filters is an interesting candidate for multi-domain suppression of ambient light. Such transceiver system may additionally operate with binary data modulated with interference tolerant modulation schemes. Furthermore, in real-world scenarios, multi-dimensional sources of interference exist concurrently. The interference could be from direct sunlight, a DC powered LED, an AC powered light source or from another active VLC transmitter operating in the vicinity of the receiver. To cater for all these interferences, a multi-dimensional suppression model is vital to establish a robust communication link. An interesting study could be to add another layer of optics by integrating optical filter/ concentrator to further enhance the suppression capability of the system.

As an example, using the circuit of Fig. 2(d), without considering the effect of linear polarizers, the total photocurrent suppression of 100 μA has been demonstrated in electronic domain [31]. If we consider the effect of polarization filtering with typical efficiency of 90%, the photocurrent suppression by the same circuit increases up to 145 μA. Furthermore, by implementing an interference tolerant modulation scheme such as geometrical or circular CSK constellation [48], much larger suppression of ambient current is possible. To recapitulate, large-scale suppression of ambient light is possible and supported by the integration of multiple methods in various physical domains.

For designing the next-generation VLC systems with CSK modulation and camera-based receivers, advanced modulation and coding techniques can be used to further enhance robustness against ambient light noise sources, increase data bit rates, and expand communication ranges. For example, diversity combining techniques can be implemented at the receiver side by capturing and processing transmitted optical signals from both vehicle lights; dynamic link adaptation can be implemented based on a feedback channel to change the modulation scheme order and coding level in real-time as a function of the measured channel conditions at the receiver side; and advanced multiple antenna techniques can be designed to allow for diversity and multiplexing trade-off gains by taking advantage of the spatial domain of the LED array of pixels at the transmitter side. This will require the use of CIS based receivers over those with photodiodes and hence the provision of electronic suppression methods at pixel or column level can significantly remove the ambient light at the front-end stage of visible light receivers.

Also, the 1400 *nm* communication link which is inherently more robust to sunlight, can co-exist with other visible light transceivers operating under 400 *nm* – 750 *nm* wavelength. One drawback to such a system is the use of InGaAs detectors which present a higher capacitance per unit area than visible Silicon equivalents. This constrains a 1400nm link to small detection areas and therefore high source powers are required to achieve data rates much greater than outlined in this paper. Therefore, Laser-based sources in the 1400nm region could be used to increase data rates for such links. Such systems have been explored within the fiber-based domain with small form-factor pluggable transceiver (SFPS) operating at 1370nm, facilitating gigabit Ethernet connections. For use in vehicular VLC channels, the presented data rate of 1400 *nm* link in our design is sufficient. For other outdoor VLC systems, the proposed link may be used as a handshake channel to begin wide-band communication via other VLC links. Safety critical, identity sharing and communication protocol data may be transmitted using 1400 *nm* channel whereas higher data rates may be established via conventional VLC channels operating concurrently with the 1400 *nm* link in future communication systems.

Recently, some machine learning techniques, such as deep learning, and reinforcement learning have been applied to VLC systems to improve the signal reception and increase

TABLE I
SUMMARY OF TECHNIQUES USED FOR THE SUPPRESSION OF AMBIENT LIGHT IN OUTDOOR VLC RECEIVERS

Physical domain	Reference	Brief description	Performance metric	Author comments
Electronic	[29]	Fully differential resistive TIA with shunt feedback to reject DC photocurrent	5μA DC rejection achieved	Electronic feedback and/or shunting of direct current is possible and should always be employed at the input stage of VLC receivers to cancel the effect of ambient sunlight and other optical noise sources. Many of these techniques can easily be combined with other methods discussed in section III, IV and V.
	[30]	Fully differential resistive TIA with floating active inductors to block DC	Up to 50 μA DC rejection shown	
	[31]	Current-mirror based complimentary channels to block unpolarized light and cancel common-mode DC via charge transfer amplifier	100 μA DC rejection possible	
	[36]	Average voltage tracking circuit is used to cancel the effect of ambient light in low-SNR receivers	1 Mbps error-free communication at SNR of -2.7dB	
Optical	[38]	LED headlamp as transmitter and photodiode with color filter and lens as receiver	Data rate of 10 Kbps was achieved at 20m in clear day light	Discrete polarization filters and/or on-chip polarization filtering maybe employed to suppress the ambient photocurrent in optical domain. Complimentary VLC channels in [31] may further be developed to completely cancel the effect of ambient sunlight and other optical noise sources.
	[39]	Red LED as transmitter and an array of three photodiodes with Fresnel lens as receiver	Data rate of 1 Kbps was achieved at 1m in fog	
	[40]	A pair of LEDs as transmitter and a pair of photodiodes as receiver with polarizing filters in between	Data rate of 20 Kbps was achieved at 0.8m under bright optical interference	
Communication or Modulation	[43]	Manchester encoding is compared with NRZ modulation technique at the transmitter end and performance is analyzed in the presence of optical noise including AC power LEDs	Manchester encoding achieving 2.5 Mbps is resilient to low frequency optical interference compared to NRZ	Diversity combining and/or link adaptation modulation techniques maybe investigated in addition to interference tolerant modulation techniques like [47], [48] to suppress the effect of ambient light. With the recent advances in machine learning and other AI techniques [60], real-time adoption of the most interference-tolerant coding or modulation method for specific application scenario is possible [62]. This area has a lot of potential to explore.
	[44]	OFDM is utilized as modulation technique and performance is analyzed in the presence of optical noise including AC power LEDs	OFDM achieves 12 Mbps, however performance degradation occurs with spectral overlap of interference and OFDM subcarrier	
	[47]	Color Shift Keying (CSK) is utilized as the modulation technique and is compared with OOK and PAM.	Compared to OOK and PAM, circular 4-CSK achieved better noise resilience	
Wavelength	Section V [this paper]	Operating an optical link at 1400nm is much more robust to the effect of ambient sunlight than a visible light transceiver operating at 400~750nm.	Mean BER do not vary more than 2σ between dark and direct sunlight conditions in a 1400nm optical link	1400nm optical link is tolerant to ambient sunlight and hence could be used as a handshake or auxiliary channel to transmit safety-critical data in VLC transceivers

the system performance [52]–[61]. Outdoor atmospheric turbulence may be compensated like [62], or nonlinear distortion minimized like [63] when combining the various ambient light suppression techniques in a single VLC system.

VII. Conclusion

We discuss the suppression methods of optical interference and suggest multiple ways to avoid VLC receiver saturation in four different physical domains – electronic, optical, wavelength and communication. Electronic circuits can effectively shunt, bypass or cancel the effect thereof ambient light which often appears in the form of a slow-varying or a DC current and thus are easily separable from a high-speed optical signal. The inclusion of polarization filters augments the robustness of the communication link against the unpolarized interferences by exploiting the optical domain characteristics of visible light. The provision of 1400 *nm* wavelength emitting composite LEDs provide unique opportunity to employ this band (inherently robust to sunlight) for sending safety critical data or handshaking information between other VLC channels. Last but not the least, color shift keying (CSK) and other modulation or channel coding techniques can be used to strengthen the robustness of VLC link against ambient light noise sources.

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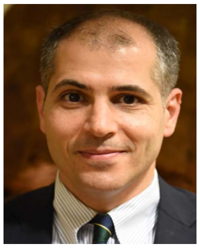

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